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United States Air Force Academy

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Revision 3  
October 2002

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# STRUCTURAL VERIFICATION REPORT

FALCONSAT-2

Small Satellite Research Center  
Department of Astronautics  
U.S. Air Force Academy, CO 80840

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**SIGNATURES****Customer Payload:** FS-2 Spacecraft**Customer:** U.S. Air Force Academy (USAFA), Space Test Program (STP)**Date:** October 2002**Customer Approval:**

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**REVISIONS**

<b>Revision</b>	<b>Description</b>	<b>Date</b>	<b>Approval</b>
1	Final Draft	5/28/02	
2	Revised Final Draft	6/05/02	
3	Revised to include reports on FM testing and testing of the redesigned S-band antenna	10/11/02	

## EXECUTIVE SUMMARY

Structural verification for FalconSat-2 (FS-2), a small satellite scheduled for launch, date TBD, with the Space Transportation System, is complete. Analysis is complete, and all margins of safety are positive.

Qualification testing is done; a dedicated nonflight unit completed qualification testing in February 2002, and the structure showed no evidence of failure. Two small antennas suffered material fatigue failures during qualification random vibration test. They were subsequently redesigned.

The Flight Model (FM) of the full-up FS-2, with redesigned antennas, was acceptance vibration tested in July 2002. With the exception of the redesigned S-band antenna, the FM passed all testing. A solder joint in the S-band antenna suffered a fatigue crack, so the antenna was once again redesigned.

In September 2002, the qualification and flight models of the final S-band antenna were successfully tested for qualification and acceptance vibration environments, respectively. The VHF antenna, redesigned as a simple wire whip, was insignificantly stressed in the July FM test, so we concluded it was not necessary to test a dedicated VHF antenna for qualification.

FalconSat-2 is the third in a series being developed in a small-satellite program at the United States Air Force Academy, following FalconGold and FalconSat-1, and is the first of the series to be launched aboard the Space Shuttle. The purpose of this program is to teach cadets by getting them involved in real space missions. Dr. Jerry Sellers is program manager.

Structural verification for FalconSat-2 was the responsibility of Dr. Ron Humble, Chief Engineer for the FalconSat program, and Mr. Tom Sarafin, a consultant to the program. Between them, they have 45 years experience in the space industry.

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## 1. INTRODUCTION, PURPOSE AND SCOPE

This report documents compliance with NASA's structural verification requirements for the FalconSat-2 (FS-2) program at the United States Air Force Academy (USAFA), according to the FS-2 structural verification plan (USAFA-FS2-SVP-01). The purpose of this report is to document how the FS-2 program has verified that FS-2 is structurally safe to handle, transport, launch aboard the Space Shuttle, and eject from the Shuttle cargo bay. In this context, "safe" means that FS-2 will not jeopardize ground-support personnel, the Shuttle or its crew, or any other payloads within the Shuttle. A separate report (USAFA-FS2-FCCR) documents compliance with fracture-control requirements.

FS-2 will fly as a Hitchhiker (HH) payload, mounted to the Pallet Ejection System (PES), inside a canister. FS-2 is planned to eject from the canister in low-Earth orbit, but, in case something goes wrong that prevents ejection, FS-2 has been designed and verified to withstand landing as well as the launch and space environments.

## 2. APPLICABLE DOCUMENTS

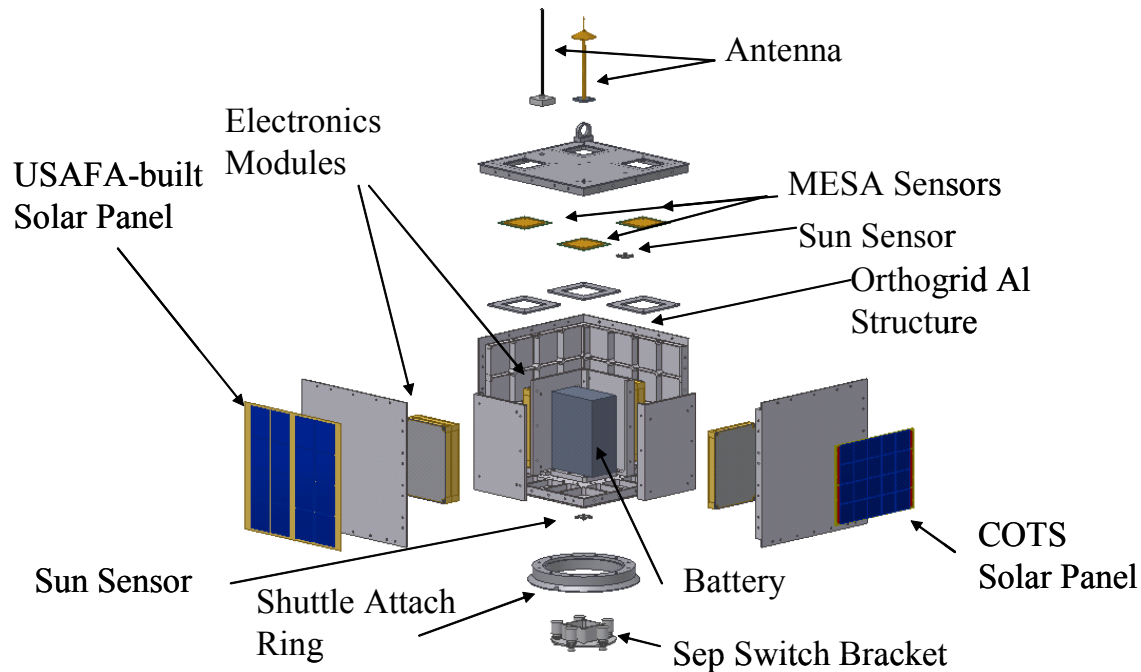
The documents listed below apply to this report to the extent specified herein.

- Customer Accommodations and Requirements Specification (CARS), 1999. NASA Goddard Space Flight Center.
- MSFC-STD-3029, May 2000. "Design Criteria for Controlling Stress Corrosion Cracking"
- USAFA-FS2-EMTR, May 2001, FalconSat-2 Engineering Model Test Report
- USAFA-FS2-SVP-01, June 2001 "Structural Verification Plan, FalconSat-2"
- USAFA-FS2-TR-QM, April 2002, Qualification Model Test Report, FalconSat-2
- USAFA-FS2-TR-FM, October 2002, Flight Model Test Report, FalconSat-2
- USAFA-FS2-SAntTR, October 2002, S-band Antenna Qualification and Acceptance Vibration Test Report
- USAFA-FS2-FCCR-23. May 2002, "Fracture Control Compliance Report, FalconSat-2"

## 3. FALCONSAT-2 STRUCTURE DESCRIPTION

The FS-2 structure consists of a nearly cubic box, approximately twelve inches per side. The six walls are made of 6061-T6 and 6061-T651 aluminum plate, machined in orthogrid patterns, and are attached with threaded fasteners. Solar arrays are bonded and bolted to the four side walls, and the top wall supports the Miniature Electrostatic Analyzer (MESA) instruments, two small antennas, and a lug for ground handling. A four-sided column inside the spacecraft, with each side machined from 6061-T6 aluminum plate, is used to support the rest of the FS-2 equipment. The column bolts to the box's base plate, which in turn bolts to an adapter ring. This ring provides the interface to the PES, attaching with a Marmon band. Figure 1 shows the structural configuration.

All structural parts, with the exception of the adapter ring, were fabricated by machining at USAFA. GSFC made the ring out of an aluminum alloy (6061-T651) with high resistance to stress-corrosion cracking.



**Figure 1: FalconSAT-2 Structural Configuration.**

#### 4. VERIFICATION APPROACH AND STATUS

For structural design and verification, the FalconSat philosophy is to use a building-blocks approach by testing early and often. The test program for FS-2 consists of development testing of an engineering model, qualification testing of a qualification model, and acceptance testing of the flight model. Analysis has been used to steer the design, simplify testing, interpret test data, and satisfy NASA's safety requirements.

Structural verification is complete. Analysis is complete, and all margins of safety are positive, as explained in Sec. 6.

Qualification testing is done; a dedicated nonflight unit completed qualification testing in February 2002, and the structure showed no evidence of failure. Two small antennas suffered material fatigue failures during qualification random vibration test. They were subsequently redesigned.

The Flight Model (FM) of the full-up FS-2, with redesigned antennas, was acceptance vibration tested in July 2002. With the exception of the redesigned S-band antenna, the FM passed all testing. A solder joint in the S-band antenna suffered a fatigue crack, so the antenna was once again redesigned.

In September 2002, the qualification and flight models of the final S-band antenna were successfully tested for qualification and acceptance vibration environments, respectively. The VHF antenna, redesigned as a simple wire whip, was insignificantly stressed in the July FM test, so we concluded it was not necessary to test a dedicated VHF antenna for qualification. Section 7 provides more details on structural testing.

Table 1 summarizes the status of compliance.



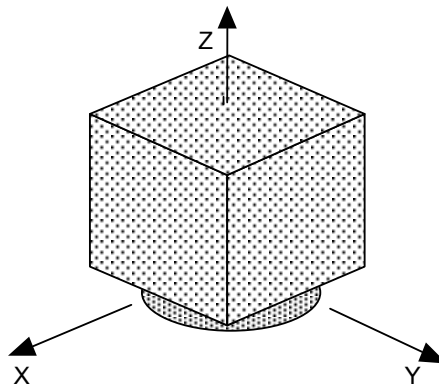
**Table 1: Status of Compliance.**

The requirements listed in this table are from the FS2 Structural Verification Plan (USAFA-FS2-SVP-01). Refer to Sections 6.0 and 7.0 herein for more extensive summaries of analyses and tests, respectively. The vectors of the coordinate system used for mass properties are given in Figure 2.

<b>Requirement</b>	<b>Verification Method</b>	<b>Statement of Compliance</b>
3.1 Strength--FS-2 shall have enough strength to withstand the highest load experienced during its life cycle.	Test and analysis. Sine-burst and random vibration tests for both qualification and acceptance, and stress analysis of critical areas.	The QM structure passed all tests (see Sec. 7.0), and all margins of safety are positive (see Sec. 6.0).
3.2.2 Random Vibration	Test. Random vibration tests, qualification and acceptance	The structure passed qualification testing; two antennas failed, were redesigned, and have passed testing.
3.2.3 Shock	Test. Qualification shock test on dedicated unit.	QM shock testing completed in Feb 2002.
3.2.4 Temperature extremes during abort landing	Analysis.	The structure is all aluminum alloy, so temperature changes will cause negligible stress. Estimated temperature range of +102 to -30C would have negligible effect on material properties.
3.3 Fundamental frequency—must deliver correlated finite-element model if the fundamental frequency is less than 50 Hz.	Test. Sine-sweep test in each of three axes.	The fundamental frequency measured during FM testing was 148 Hz, satisfying the requirement.
3.4.1 Max. weight of 150 lb	Weigh the assembly	The FM was weighed at 43.25 lb (a mass of 0.112 lb-s <sup>2</sup> /in), counting the separation ring.
3.4.2 Center of gravity--The C.G. must be laterally within a 0.25" radius of the center of the separation ring and must be within 10.25" of the separation plane.	Measurement	The C.G. was measured for the FM and found to be as follows, as located from the center of the separation plane <sup>1</sup> : X = -0.019 in., Y = -0.010 in., Z = 6.174 in.

<sup>1</sup> The FM test report gives a Z coordinate of the measured C.G. as 4.924 in., as measured from the center of the aft (-Z) surface of the base plate. The Z coordinate reported in Table 1, herein, includes the addition of the thickness (1.250") of the separation ring so that it is the location relative to the center of the separation plane.

3.4.3 Mass moments of inertia	Measurement	Mass moments of inertia were measured for the FM and found to be as follows (about the C.G.): $I_{xx} = 3.496 \text{ lb-s}^2\text{-in}$ $I_{yy} = 3.640 \text{ lb-s}^2\text{-in}$ $I_{zz} = 3.071 \text{ lb-s}^2\text{-in}$
3.5 Materials--All structural parts shall be made of materials listed in MSFC-STD-3029, which have high resistance to stress-corrosion cracking.	Inspection	A detailed materials list was provided to GSFC (USAFA-FS2-ML-23).
3.6 Fasteners--All fasteners shall meet the requirements of GSFC 541-PG-8072.1.2	GSFC will inspect and control fasteners, USAFA will control installation processes	Fasteners were provided by GSFC per GFSC 541-PG-8072.1.2. Installation and removal of fasteners have been noted in the appropriate assembly log.
3.7 Fatigue life--The FS-2 structure shall have adequate fatigue life to withstand all mission life-cycle events without catastrophic failure.	Test. Qualification random vibration testing on a dedicated unit.	Qualification testing of the QM was successful for everything other than the VHF and S-band antennas. These antennas have been redesigned. The S-band antenna passed qualification vibration testing. The VHF antenna is not significantly stressed by random vibration and thus was tested for acceptance only.
3.8 Fracture control	Analysis	See the Fracture Control Compliance Report (USAFA-FS2-FCCR-23)



**Figure 2: FalconSAT-2 Body Axis Coordinate System**

The process used for developing the FS-2 structure was as follows:

1. Develop a conceptual configuration for FS-2.

The conceptual configuration established load paths and locations for the spacecraft's equipment.

2. Design a structure for an engineering model (EM).

The EM was a development unit. Its purpose was to pathfind manufacturing, integration, and test; identify design improvements; and acquire information that would help make the flight design more predictable. The EM structure was designed without the aid of analysis to be representative of the eventual final design but considerably stiffer and heavier. The machined base plate (see Fig. 1) is the critical structural part, stressed by bending, mostly under lateral (X and Y) loading. It was designed as a nearly solid 0.75"-thick aluminum plate to make its failure unlikely during vibration testing.

3. Simplify the specified loads by reducing them to equivalent single-axis loads for test.

The Customer Accommodations and Requirements Specification (CARS) [NASA, 1999] specifies limit loads of 11g in each of three orthogonal directions, along with  $85 \text{ rad/s}^2$  rotational acceleration acting in each axis, all acting simultaneously. Because each of the six axes of specified accelerations (three translations and three rotations) can act in any direction, together they present 64 ( $2^6$ ) load cases. The FS-2 program decided to simplify this set of load cases by reducing them to equivalent single-axis accelerations that could be easily assessed by analysis and introduced by test on an electrodynamic shaker. The resulting limit load cases were  $\pm 25 \text{ g}$  applied uniformly in each of the three axes of the coordinate system defined in Figure 2. Appendix A of the FS-2 Structural Verification Plan documents the derivation of these load cases.

4. Test the EM for sine sweep, random vibe, and sine burst.

The EM weighed about 47 lbs, counting the adapter ring. We instrumented the EM with accelerometers, as defined in Sec. 7.1.

In each axis, the EM was tested in the following sequence:

- Low-level sine sweep from 20 to 2000 Hz to determine natural frequencies

- Random vibration, at incrementally higher levels to ensure the input matched the specified power spectral density (PSD) within acceptable tolerances, culminating at full qualification levels for one minute.
- Low-level sine sweep to ensure the dynamic characteristics had not significantly changed.
- Sine burst at 30 Hz, at incrementally higher levels until the full qual level (35 g) was reached.
- Low-level sine sweep.

5. Interpret test results and gain knowledge.

The purpose of development testing was to gain knowledge that would help us design the flight structure. Of main interest was fundamental frequency, approximate mode shapes, response to random vibration, and whether the EM still operated after testing.

The key thing we learned from EM testing was that the specified random-vibration environment stressed the structure far more severely than the simplified quasi-static accelerations (+/-25 g). The highest loads were from response of the 182-Hz fundamental mode of vibration, which was a lateral, rocking mode. We derived limit load cases from the measured accelerations and designed the flight to them. The analysis documented in Appendix B is based on revised load cases based on the measured response of the QM during qualification testing, in which the specified environment was notched, as explained in Sec. 7.

6. Develop a simple finite-element model.

From the start, we planned not to be dependent on a detailed finite-element model. There were two reasons for this: First, the cadets did not have the necessary knowledge and would not have learned much by having a consultant generate such a model for them. Second, we believed such a model was not necessary and was not cost-effective for the design we envisioned.

Still, we used the results of development testing to develop a simple, semi-correlated finite-element model, which we subsequently modified along with the evolving design to provide confidence. This simple model, developed in this way, gave us reasonably reliable predictions of fundamental frequency and response to random vibration as we modified the design.

7. Design the flight structure.

Development testing identified several goals for design of the flight structure:

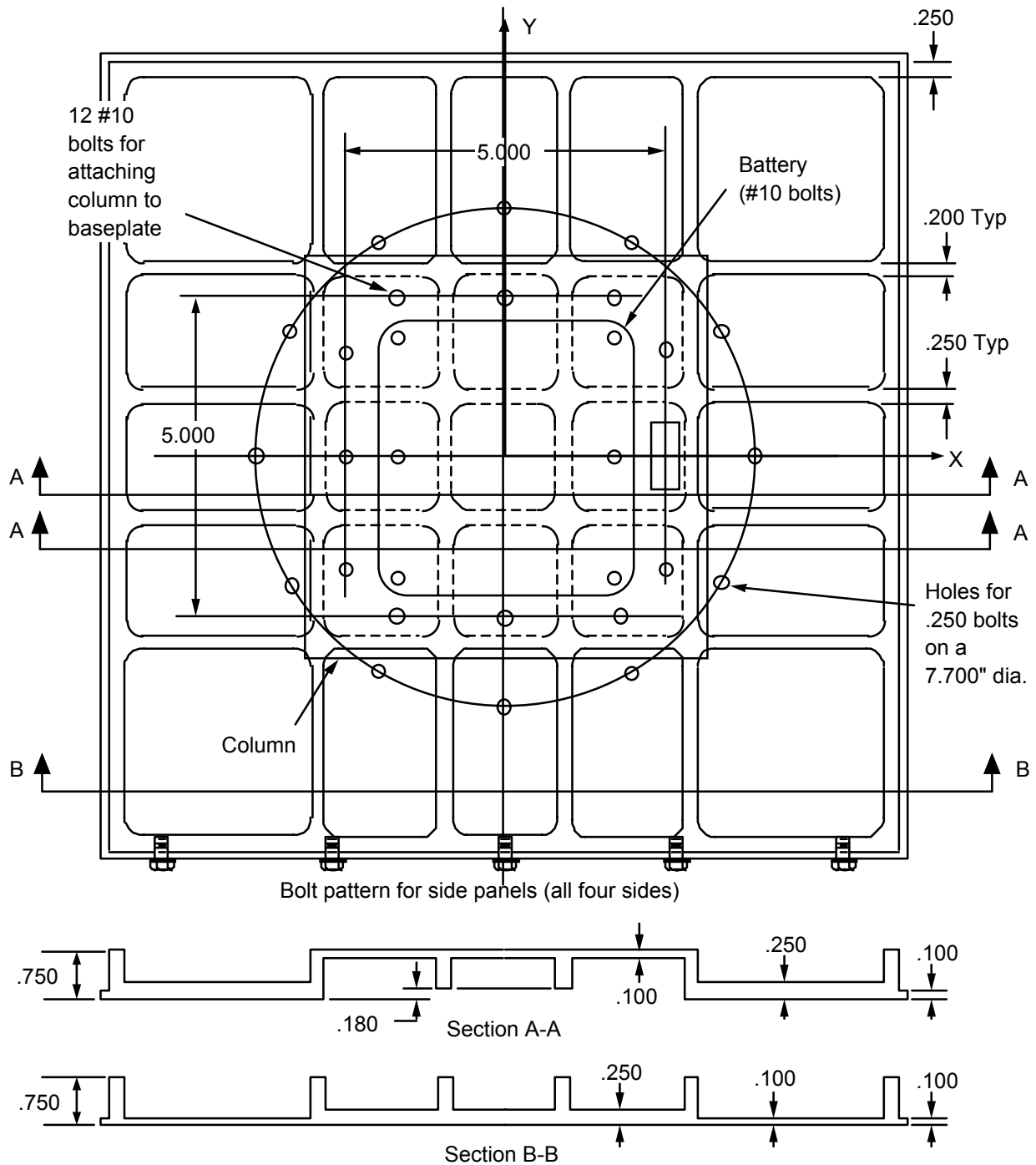
- Reduce weight—Although weight was not critical, reducing weight from that of the EM, through a more efficient structure, would serve two purposes: reduce structural loads (forces and moments) for given acceleration and make the spacecraft easier to handle on the ground.
- Reduce the fundamental frequency—Doing so should lower the peak response of the rocking mode to base-driven random vibration. We wanted to stay above 50 Hz to keep structural verification as simple as possible. To account for uncertainty, we set a target of at least 80 Hz for design, based on prediction by a simple finite-element model.
- Increase damping—Raising the damping for the rocking mode would reduce its peak response to random vibration. Unfortunately, designing damping into the structure with

viscoelastic materials was beyond our capability and budget, so there was not much we could do here.

For developing the final design, we continued to keep things as simple as possible, with the following process:

- Keep load paths simple and direct, and use proven designs for joints. In other words, we designed a structure that we could analyze easily.
- Use hand analysis to size the structure for strength requirements.
- Plan how to satisfy fracture-control requirements and, if needed, modify the design accordingly.
- Develop a simple finite-element model, using assumptions similar to those used for generating the semi-correlated model of the EM.
- Predict modes of vibration and responses to specified random vibration; compare with targets and assumptions.
- Iterate the design, as needed.

The base plate is the part that will be most highly stressed during launch. We decided to machine it out of  $\frac{3}{4}$ "-thick 6061-T651 plate, which is low in cost, readily available, ductile, and resistant to corrosion. We used an orthogrid pattern of machined ribs, which could easily be analyzed as beams. Figure 3 shows the design of the base plate.



**Figure 3: Design of the FS-2 Base Plate**

We also refined the designs of the four side panels and the top panel used for the EM, but, instead of analysis, the refinement was based on judgment, producibility, and good engineering practices. For example, the material under the bolts used to join the side panels was thinned down to 0.100" in order to make the attachments bearing critical rather than shear critical—a

good practice for avoiding failure from uneven load distribution between fasteners. Knowing the side and top panels were not highly loaded, we thinned the machined ribs (also an orthogrid pattern) from 0.250" to 0.100", based on judgment. We kept the side panels 0.75" thick (rib height) so they would have enough bending stiffness to keep shear stresses low in the adhesive used to attach the solar panels (cells bonded to thin sandwich panels).

8. Build and test a qualification model (QM).

In keeping with the philosophy of true qualification testing, the QM was built at USAFA to the design intended for the flight unit and with the processes intended for the flight unit. Qualification testing of the QM was completed in February 2002, and included tests for thermal vacuum, thermal cycling, sine sweep (to determine natural frequencies), sine burst (uniform acceleration), random vibration, and shock. Section 7 summarizes the QM test program.

Qualification random-vibration testing is our method of verifying fatigue life for the flight model. Fatigue life can't be verified by testing a flight unit because, after testing, the unit still must have enough fatigue life to make it through the mission. Testing a dedicated, nonflight unit to environments that are more severe and of longer duration than the flight unit will ever see does not prove the flight unit has adequate fatigue life, but it provides a great deal of confidence when both units are built to the same recipe. For FS-2, we tested the QM to a random-vibration environment three decibels above the acceptance environment, for three minutes per axis. The acceptance test program for the Flight Model (FM) includes random-vibration testing to acceptance levels at one minute per axis.

9. Interpret test results and gain knowledge.

The QM structure passed qualification testing, so the design was not modified for the flight structure. The S-band and VHF antennas failed in material fatigue and were subsequently redesigned. Dedicated builds of the new antenna designs will receive qualification testing. For details of the QM test program, see Sec. 7.

10. Build and test the Flight Model (FM).

The FM passed acceptance testing with one exception: The S-band antenna suffered a fatigue crack in a solder joint. This antenna was once more redesigned, this time with thorough supporting analysis, and was successfully tested for qualification and acceptance.

## 5. CRITERIA FOR STRUCTURAL DESIGN AND ANALYSIS

The following ground rules and standards were used at USAFA. They applied in addition to the requirements defined in Section 3 of the SVP for the purpose of ensuring quality and structural integrity. Along with the criteria are statements of compliance for FS-2.

### 5.1 Factors of Safety and General Strength Criteria

Limit load is defined as the highest expected load for an event at a statistically appropriate probability. Flight limit loads are defined by NASA as the nominally expected peak load plus three times the standard deviation. Flight limit loads are the higher of +/-25-g uniform acceleration applied separately in each of the axes defined in Figure 1 (see USAFA-FS2-SVP-01 for justification) and the predicted limit response to acceptance-level random vibration. The *limit response to random vibration* is defined

as three times the predicted root-mean-square (RMS) response for ductile failure modes. For brittle failure modes, the limit load for random vibration will be the RMS value multiplied by a statistically appropriate number greater than three.

The following criteria apply to strength analysis for all loading events:

- At the *design ultimate loads*, which are limit loads multiplied by the ultimate factor of safety, analysis must show there will be no catastrophic rupture or collapse.
- At the *design yield loads*, which are limit loads multiplied by the yield factor of safety, analysis must show there will be no permanent detrimental deformation.

Factors of safety are as defined in Table 2.

**Table 2: Factors of Safety for Structural Analysis**

Application	Ultimate	Yield
Flight structure, flight loads	1.4	1.1
Flight structure, qualification test loads	1.25	1.0
Flight structure, ground-handling loads	3.0	2.0
Ground support equipment	5.0	3.0

Ground-support equipment shall be proof-tested to twice the limit load for ground handling.

**Statement of compliance:** The above criteria were used to calculate margins of safety, as summarized in Sec. 6.0 and detailed in Appendix B. Derivation of limit loads per these criteria is documented in Appendix A.

## 5.2 Material Properties

Materials allowable for stress analysis shall be A-Basis (99% probability at 95% statistical confidence) from MIL-HDBK-5G.

**Statement of compliance:** The stress analysis (Appendix B) was done with A-basis allowables from MIL-HDBK-5G. Appendix F herein documents the derivation of an allowable load for pull-out strength of inserts, with the intent of meeting A-basis requirements.

## 5.3 Fastened Joints

### 5.3.1 Fastener Size

All main load-carrying threaded fasteners used in structural applications shall be of size #10 (0.190" diameter) or greater.

**Statement of compliance:** Satisfied.

### 5.3.2 Fitting Factor

Strength analysis of fastened joints shall include an additional factor of safety, called a fitting factor, of 1.15. This factor shall apply to ultimate analysis of all potential failure modes associated with joints,



such as bolts, nuts, inserts, bearing stresses, net-section stresses, and shear tear-out. The fitting factor also will apply for yield analysis when alignment is critical.

**Statement of compliance:** The stress analysis (Appendix B) includes fitting factors as specified above.

### 5.3.3 Preload

All structural joints using threaded fasteners shall be designed to ensure adequate clamping force such that there will be no gapping at limit load. In addition, if gapping could cause catastrophic failure, the joint shall be designed to ensure no gapping at design ultimate load. Preload will be developed by controlling the installation torque, with the specified torque being justified by analysis and supporting test data.

**Statement of compliance:** Section B.6 of Appendix B documents the analysis showing that all threaded fasteners with significant axial applied load are preloaded highly enough to ensure no gapping at limit.

### 5.3.4 Locking Feature

All threaded fasteners shall have locking features that are effective at preventing relative rotation and preload loss.

**Statement of compliance:** All threaded fasteners have effective locking features:

- The Spiralock internal thread form, which is a proven locking mechanism (Ref. Kerley), is used for attachment of the exterior structural panels, the internal column walls, and the column assembly to the base plate.
- NAS1805 self-locking nuts are used for the 1/4" bolts attaching the base plate to the separation ring, the #10 bolts attaching the battery to the base plate, and the #10 bolts attaching the MESA sensor assemblies to the top panel.
- MS21043 self-locking nuts are used for the #4 bolts attaching the S-band antenna to the top panel, the #6 bolts attaching the sun sensors, and the #6 bolts attaching the solar panels to the structural panels.
- RTV on fastener head and body was used to lock other small, lightly loaded fasteners, such as #4 screws on electrical connectors.

### 5.3.5 Tapped Holes and Inserts

To ensure tapped holes and inserts have adequate pull-out strength for hardware built at USAFA, the FS-2 program will take two steps:

1. Conduct development tests to establish processes for tapping holes and installing inserts and derive statistically based allowable strengths.
2. Establish an in-house certification program in which anyone tapping holes or installing inserts in flight hardware must demonstrate mastery of the process with test specimens.

Good practice is to ensure the tapped hole or insert can fully develop the strength of the bolt. Bolt tensile failure is usually more ductile than thread shear, and ductile failure modes lead to robust structures. If the tapped hole or insert is not at least as strong as the bolt, the FS-2 program will design to protect against brittle failure resulting from uneven load sharing between fasteners and from fastener preload.

**Statement of compliance:** The first step was accomplished with a test of twelve specimens, as documented in Appendix F. The second step was also accomplished in that the same person who installed inserts for this test installed all of the inserts in flight hardware, using the same procedure.

The allowable load for #10 inserts derived in Appendix F is 1900 lb, as compared with an allowable tensile load for the bolt of 3200 lb. However, the testing documented in Appendix F showed that the failure mode was quite ductile, and preload did not reduce the strength under applied loads. As shown in Appendix B, none of the inserts will experience significant load during the mission and are thus adequate.

## 5.4 Dimensional Tolerances

Structural analysis shall consider the effects of dimensional tolerances and potential misalignment. Material thickness used for strength analysis shall be the lesser of ...

- Nominal or 1.1 times minimum for tension, shear, and block compression
- Nominal or 1.05 times minimum for plate bending, for which stress is inversely proportional to thickness squared
- Nominal or 1.03 times minimum for compression of a panel or shell, for which buckling stress is inversely proportional to thickness cubed
- Minimum for pressurized systems

These criteria are intended to simplify analysis while also ensuring that the potential reduction in strength from dimensional tolerances is limited to 10%. For the best prediction of vibration modes and load distribution, finite-element models should be based on nominal thickness. Stresses predicted with nominal-thickness models shall be modified as needed to meet the above criteria for strength analysis.

**Statement of compliance:** Satisfied, as documented in Appendix B.

## 6. STRUCTURAL ANALYSIS SUMMARY

### 6.1 Methodology

Structural analysis for final verification was based on the criteria defined in Sec. 5 and limit loads that were derived from qualification testing. These loads are more severe than the quasi-static accelerations specified in the CARS. (See Appendix A herein for documentation of the loads derivation.) We defined the limit load for ground handling as the weight lifted.

Analysis was for potentially critical areas of the structure only, based on judgment. The analysis used classical hand methods, including beam theory and industry-standard, semi-empirical techniques. Mathcad software was used to automate the analysis so that revised loads can easily be assessed. Appendix B documents the analysis.

Instead of analysis for the ground-handling lug, we tested a dedicated lug to failure and found that it carried an ultimate load of 6225 lb, vs. a limit load of about 43 lb (the weight of FS-2) during ground handling. We did analyze the top panel of FS-2 for ground-handling loads, with the factors of safety defined in Sec. 5.1, as documented in Appendix B. The margins of safety for the top panel under ground-handling loads are positive, as summarized in Sec. 6.2. We tested the lug and top panel of the

QM to an applied load of 200 lb. The lug and top panel of the FM will be tested to an applied load of at least 100 lb. Note that, during qualification testing, the QM was lifted with the NASA-provided Pallet Ejection System attached during the shock test. The total weight was less than 100 lb, but we used 200 lb for the test to provide margin for uncertainty. The FM will not be lifted by the ground-handling lug when the PES is attached, so a test load of 100 lb is more than twice the limit load, which is the required load for proof testing.

## 6.2 Margins of Safety

Table 3 summarizes the structural margins of safety. See Appendix B for details. The margin of safety,  $MS$ , is defined as

$$MS = \frac{P}{FS(p)} - 1$$

where  $P$  is the allowable load,  $p$  is the limit load, and  $FS$  is the factor of safety. For fastened joints, per the criteria in Sec. 5.3.2, the denominator in the above equation may include a fitting factor of 1.15 as an extra multiplier. The criterion for safety is that margins of safety must be zero or greater.

**Table 3: Summary of Margins of Safety.**

These are the lowest margins of safety for the FS-2 structure associated with flight loads and ground-handling loads. The first four margins listed apply to flight loads, with factors of safety of 1.4 for ultimate and 1.1 for yield. The last margin listed applies for ground-handling loads on flight structure, with factors of safety of 3 for ultimate and 2 for yield.

Structural Part and Critical Potential Failure Mode	MS	Ultimate or Yield
Base plate—end-pad bending under bolts attaching to separation ring	+3.99	Yield
Base plate—end-pad bending under bolts attaching battery	+0.64	Yield
Base plate—bending of machined ribs	+1.41	Yield
Side panels—bearing under bolt shear at base-plate interface	+2.53	Ultimate
Top panel—end-pad bending at lug bolts under ground-handling loads (based on limit load—weight lifted—of 100 lb)	+0.39	Yield

## 7. STRUCTURAL TESTING SUMMARY

The test program for FalconSat-2 consists of three phases: development testing, qualification testing, and acceptance testing (Table 4). As of the date of this report, all testing has been successfully completed, and there are no open issues.

**Table 4: FalconSat-2 Structural Test Program**

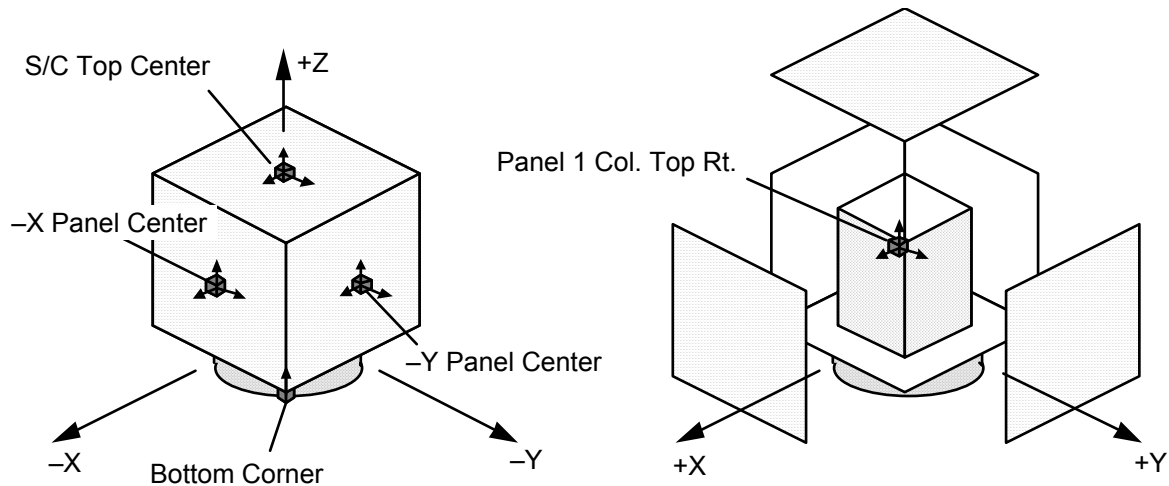
Test Phase	Test Article	Objectives	Planned Tests	Test Levels and Criteria
Development	Engineering model (representative structure, complete with nonstructural equipment)	Obtain information to improve the final design and help plan the qualification and acceptance test phases.	- Sine sweep  - Random vibration  - Sine burst	Low (used to determine natural frequencies)  3 dB above acceptance levels in each of 3 orthogonal axes  1.4 times limit acceleration in each of 3 orthogonal axes
Qualification	A test-dedicated unit built to the same design and with the same processes as the flight unit; full assembly, with all equipment	Demonstrate the FS-2 structural design is adequate for strength and fatigue life, with margin that should cover unavoidable variation in manufacturing processes.	- Sine sweep  - Random vibration  - Sine burst  - Shock	Low (used to determine natural frequencies)  3 dB above acceptance levels in each of 3 orthogonal axes, 3 minutes per axis  1.4 times limit acceleration in each of 3 orthogonal axes  6 dB above acceptance
Acceptance	Flight unit; full assembly, with all equipment	Verify process control and workmanship.	- Sine sweep  - Random vibration  - Sine burst	Low (used to determine natural frequencies)  Acceptance levels in each of 3 orthogonal axes, 1 minute per axis  Limit acceleration in each of 3 orthogonal axes

## 7.1 Development Testing

Development testing of the Engineering Model (EM) was conducted in April 2001. This test is significant for verification only in that it contributed information that helped us develop the flight-structure design. The EM weighed about 47 lbs, counting the adapter ring.

Tri-axial accelerometers were mounted at the center of the top (+Z) panel, one of the corners at the top of the internal equipment column, and the centers of two side panels (-X and -Y). A single-axis (Z)

accelerometer was put on one of the bottom corners of the box structure. Figure 4 shows the accelerometer locations. The bottom of the separation ring was mounted to an aluminum test fixture, which was then bolted to the shaker table.



**Figure 4: Accelerometer Locations for the Engineering Model**

In each axis, the EM was tested in the following sequence:

- Low-level sine sweep from 20 to 2000 Hz to determine natural frequencies. The fundamental frequency was a lateral, rocking mode at 182 Hz.
- Random vibration, at incrementally higher levels to ensure the input matched the specified power spectral density (PSD) within acceptable tolerances, culminating at full qualification levels (3 dB above acceptance) for one minute.
- Low-level sine sweep to ensure the dynamic characteristics had not significantly changed.
- Sine burst at 30 Hz, at incrementally higher levels until the full qual level (35 g) was reached.
- Low-level sine sweep.

Thermal vacuum testing was also performed, before the vibration testing. Functional testing was done before and after key tests to determine whether the QM still operated properly.

Data from vibration testing indicated that the response to X and Y random vibration stressed the primary structure considerably more than the 25-g quasi-static loads. From the data, we derived loads for the flight-model design. These loads no longer apply because we have revised the limit loads based on results of qualification testing (Appendix A).

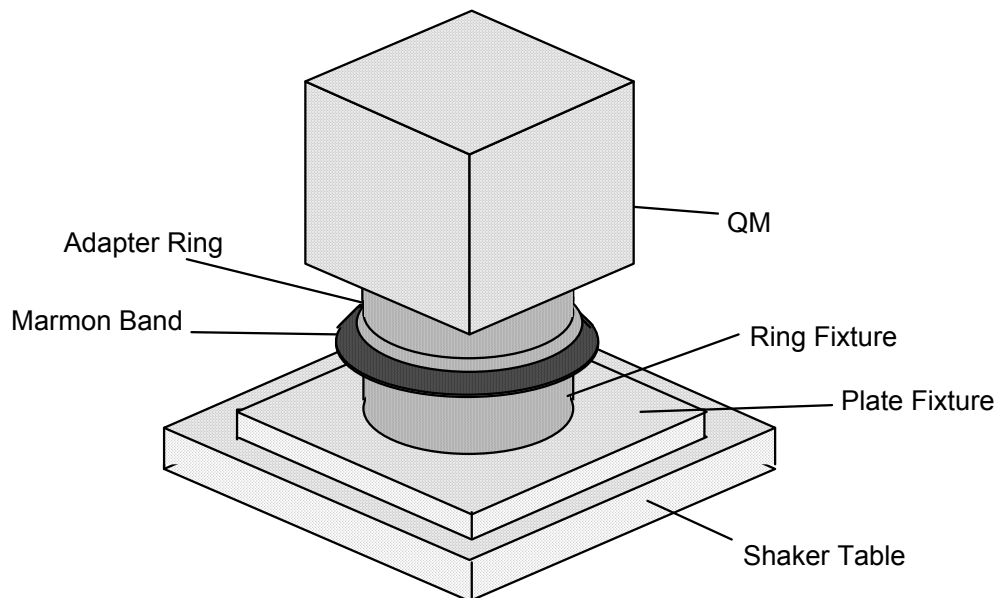
For more details on development testing, see the FalconSat-2 Engineering Model Test Report.

## 7.2 Qualification Testing

Structural qualification testing of the Qualification Model (QM) was completed in February 2002. Accelerometer locations, defined in Appendix E, were similar to those used for the EM.

The structure passed all tests, with natural frequencies showing negligible change between pretest and post-test sine sweeps. The S-band and VHF antennas suffered material fatigue failure during random vibration testing. We subsequently redesigned those antennas and plan to qualify their designs through random-vibration testing at levels derived from the response of the top panel measured during QM testing.

The configuration for QM vibration testing included a test-dedicated Marmon band and an adapter fixture for providing the proper interface for the band, as shown in Figure 5. The band was installed with a bolt preload of approximately 2500 lb, as compared to 2000 lb for the flight configuration. The extra preload was intended to keep load paths linear, given that the qualification levels of random vibration cause response accelerations about 40% higher than the maximum expected accelerations during launch.



**Figure 5: Configuration for Vibration Testing of the Qualification Model**

In each axis, the QM was tested in the following sequence, with the X axis tested first, then Y, then Z:

- Low-level sine sweep from 20 to 2000 Hz to determine natural frequencies. The fundamental frequency was a lateral, rocking mode at 157 Hz.
- Sine burst at 33 Hz, at incrementally higher levels until the full qual level (35 g) was reached.
- Low-level sine sweep to ensure the dynamic characteristics had not significantly changed.

- Random vibration, at incrementally higher levels to ensure the input matched the specified power spectral density (PSD) within acceptable tolerances, culminating at full qualification levels (3 dB above acceptance) for three minutes.
- Low-level sine sweep to ensure the dynamic characteristics had not significantly changed. After testing in each axis, this sine sweep showed the fundamental frequencies had not changed by more than 5%, which was the success criterion used.

Prior to vibration testing, the QM was tested for thermal vacuum and thermal cycling. In addition, the QM test program included a measurement of mass properties.

A shock test was also performed, in which pyrotechnic initiators were fired to allow the Marmon band to release. The initiators had 115% of the charge that will be used in the mission, with the intent being to demonstrate margin in the design. This test was not required by NASA; the FS-2 program decided to do it in order to build confidence that FS-2 will be able to operate properly after being exposed to shock. The shock environment, as measured by the QM accelerometers, proved to be relatively low, and the QM functioned properly after the test. In addition, the test demonstrated successful separation.

In the X and Y directions, the specified random vibration environment was “notched” to preclude excessive overtesting. This means that the acceleration power spectral density (PSD) was reduced near the measured fundamental frequency of the QM. Appendix D justifies the notching, although we chose not to take full advantage of the extent of notching justified. For Z-axis testing, the full specified environment was used without notching. Table 5 and Table 6 define the input PSDs used for QM vibration testing.

**Table 5: Qualification-Level PSD for Z-axis Random Vibration Testing** (Source: CARS)

Frequency (Hz)	Acceleration PSD (g <sup>2</sup> /Hz)
20	0.0125
20 – 50	+6 dB/octave
50 – 600	0.075
600 – 2000	-4.5 dB/octave
2000	0.0125

**Table 6: Notched Qualification-Level PSD for X-axis and Y-axis Random Vibration Testing**

X Axis		Y Axis	
Frequency (Hz)	PSD (g <sup>2</sup> /Hz)	Frequency (Hz)	PSD (g <sup>2</sup> /Hz)
20	0.025	20	0.025
20 – 50	+6 dB/octave	20 – 50	+6 dB/octave
50 – 123	0.15	50 – 137	0.15
123 – 177	0.03	137 – 197	0.03
177 – 600	0.15	197 – 600	0.15
600 – 2000	-4.5 dB/octave	600 – 2000	-4.5 dB/octave
2000	0.025	2000	0.025

The notching strategy defined in Table 5 is more conservative than the approach justified in Appendix D, meaning it stresses the structure more. We planned it this way to keep things as simple as possible during testing. It's based on trying to limit the stress caused by response of the fundamental mode to the stress caused by sine-burst testing. The depth of the notch needed to do this was determined from results of testing the engineering model (EM), which showed that the unnotched qual-level PSD stressed the primary structure approximately a factor of 2.6 more than the 35-g sine-burst test. The depth of the notch in Table 4 is about 8 dB, which corresponds approximately to a 2.6 reduction in stress. The width of the notch is based on judgment after reviewing the EM test results. A similar approach will be used for acceptance testing of the Flight Model (FM). As a result of this simplified approach to notching, the QM test fully met its objectives, the fatigue life of the FS-2 structure was verified, and there will be no unnecessary fatigue damage to the FM as a result of overtesting.

The QM configuration tested was not exactly the same as that of the FM, as we had planned it to be. Interference at the interface between USAFA and NASA hardware caused the plungers of the five separation switches to bottom out on the test fixture representing the NASA structure. As a result, with the Marmon band installed, the secondary load path through the switches and their mounting bracket was stiffer than it will be for flight. To avoid this interference in the flight configuration, the FM base plate was trimmed down in thickness by 0.180 in. in the center (the .180 dimension in Figure 3), where the switch bracket attaches, thus raising the plungers. This change should cause the fundamental rocking frequency to decrease for the FM.

As is the nature of response to base-driven random vibration, a reduction in natural frequency, with everything else the same, should result in reduced response acceleration because more energy would be required for the same acceleration. This means the peak moment at the interface between the base plate and the separation ring in the QM test was probably more than 3 dB (a factor of 1.4) higher than it will be in the FM test. However, the center part of the base plate, being 0.180" thinner for the FM, probably will be stressed in the FM test more than it was for the QM at the same acceptance level of random vibration. In other words, we did not qualify the design in this region, and the QM test did not verify fatigue life for this part of the structure.

From page 19 of Appendix B, the predicted limit stress in the reduced-thickness region of the base plate is 13,200 psi during acceptance testing of the FM. This is a relatively low stress. Even with a stress-concentration factor associated with the 0.03-in radius at the transition between full 0.75-in thickness and 0.57-in reduced thickness, the FM should have more than enough fatigue life to withstand mission loads after acceptance testing.

For more information on the QM test, see the FalconSat-2 Qualification Model Test Report (USAFA-FS2-TR-QM).

### 7.3 Acceptance Testing of the Flight Model

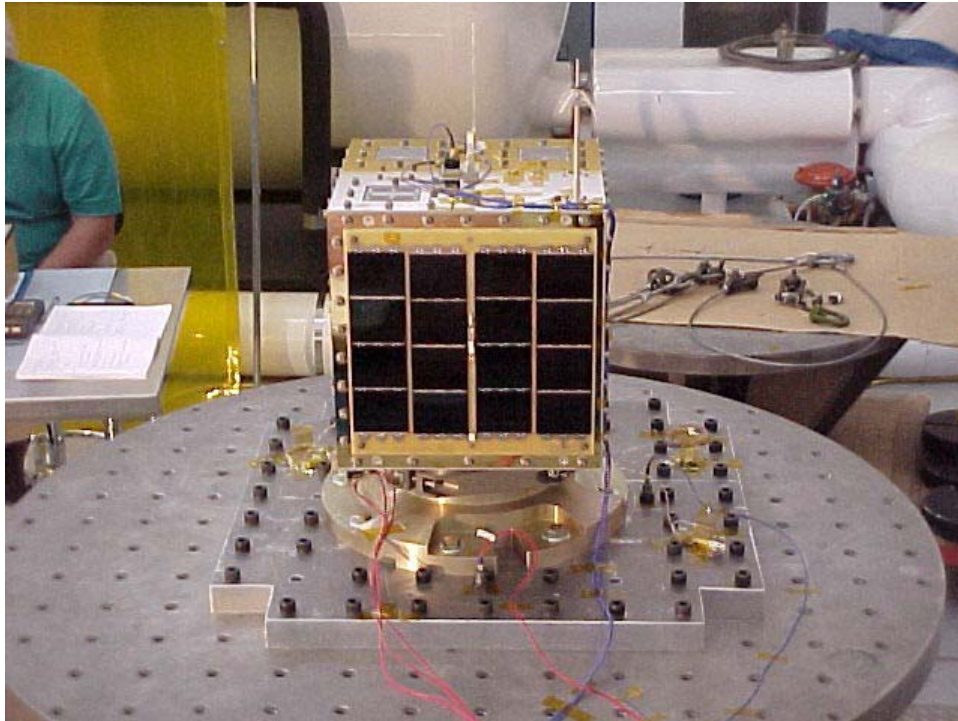
Structural acceptance testing of the Flight Model (FM) was completed in July 2002. Following is a summary of FM testing; for details, see the Flight Model Test Report (USAFA-FS2-TR-FM).

The FM was tested to acceptance-level sine burst and random vibration in the X, Y, and Z axes. The structure passed all tests, with natural frequencies showing negligible change between pretest and post-test sine sweeps. The S-band antennas suffered a fatigue crack in a solder joint during random



vibration testing. We subsequently redesigned the S-band antenna tested it separately for qualification and acceptance (Sec. 7.4).

The configuration for FM vibration testing was nearly identical to the one used for QM testing. It included a test-dedicated Marmon band and an adapter fixture for providing the proper interface for the band, as shown in Figure 5. The band was installed with a bolt preload of approximately 2500 lb, as compared to 2000 lb for the flight configuration. Figure 6 shows the FM configured for Z-axis testing.



**Figure 6: FalconSat-2 Flight Model Configured for Z-axis Acceptance Vibration Testing.**

In each axis, the FM was tested in the following sequence, with the Z axis tested first, then X, then Y:

- Low-level sine sweep from 20 to 2000 Hz to determine natural frequencies. The fundamental frequency was a lateral, rocking mode at 148 Hz. In the Z axis, the fundamental frequency was 316 Hz.
- Sine burst (at 60 Hz in the Z axis and 35 Hz in the X and Y axes) at incrementally higher levels until the full acceptance level (25 g) was reached.
- Low-level sine sweep to ensure the dynamic characteristics had not significantly changed.
- Random vibration, at incrementally higher levels to ensure the input matched the specified power spectral density (PSD) within acceptable tolerances, culminating at full acceptance levels for one minute.

- Low-level sine sweep to ensure the dynamic characteristics had not significantly changed. After testing in each axis, this sine sweep showed the fundamental frequencies had not changed by more than 5%, which was the success criterion used. The fundamental rocking mode remained at 148 Hz.

Prior to vibration testing, the FM was tested for thermal vacuum. In addition, the FM test program included a measurement of mass properties. Functional testing was used before and after the key tests to ensure the FM still functioned properly.

In the X and Y directions, the specified random vibration environment was “notched” to preclude excessive overtesting in a manner similar to that used for QM testing. Appendix D justifies the notching, although we chose not to take full advantage of the extent of notching justified. For Z-axis testing, the full specified environment was used without notching.

The FM test configuration differed from the QM test configuration, as noted in Sec. 7.2. The FM test configuration was just like the flight configuration. There was no interference at the interface between USAFA and NASA hardware, as there had been for QM testing (the plungers of the five separation switches were bottomed out on the test fixture representing the NASA structure in the QM test). This configuration difference is the reason that the fundamental rocking frequency was less (148 Hz) for the FM than it was for the QM (157 Hz).

For more information on the FM test, see the FalconSat-2 Flight Model Test Report (USAFA-FS2-TR-FM).

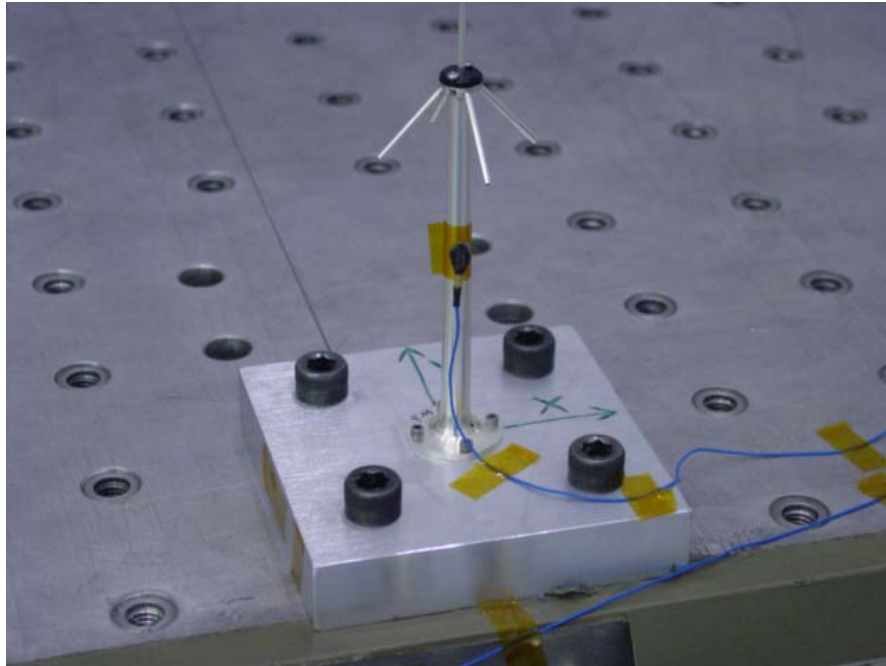
## **7.4 Qualification and Acceptance Testing of the S-band Antenna**

The S-band antenna failed in QM testing, was redesigned, and failed again in FM testing. As a result, we redesigned the antenna again, this time with detailed supporting analysis. The body (post) of the antenna is now a one-piece part machined from brass (no solder joints).

In September 2002, a dedicated qualification model of the redesigned antenna passed qualification vibration testing (3 minutes per axis), and the flight model passed acceptance testing (1 minute per axis). These tests were conducted with the antenna bolted to a test fixture, which was separately bolted to the shaker table (Figure 7). The absence of the full FS-2 structure required that the test environment be modified to ensure a good test. Because of limitations of the test equipment, the test environment in the X and Y axes had to be broken down into low-frequency and high-frequency tests.

The antennas passed vibration testing. There was no visual evidence of cracking, the fundamental frequencies remained constant, and the antennas functioned properly after testing.

For detailed information on the redesign and the test as well as the supporting analysis, see the S-band Antenna Qualification and Acceptance Vibration Test Report (USAFAA-FS2-Sant-TR) and its appendices.



**Figure 7: New Flight Model of the S-band Antenna Set Up for Acceptance Vibration Testing in the Y Axis.**

## 8. CONCLUSIONS

Structural verification is complete, with no open issues. Our conclusion is that FalconSat-2 satisfies NASA's criteria for structural verification and is thus structurally safe for launch in the Shuttle as a Hitchhiker payload.

## 9. REFERENCES

- Kerley, J., September 1984. "Report on Dynamic and Static Testing of Kaynar Spiralock Microdot Nuts." Goddard Space Flight Center.
- MIL-HDBK-5G, November 1994. "Metallic Materials and Elements for Aerospace Vehicle Structures." Department of Defense.

## 10. ACRONYMS

CARS	Customer Accommodations and Requirements Specification (see list of applicable documents)
C.G.	Center of gravity
FM	Flight Model (FalconSat-2 flight unit)

FS	Factor of Safety
FS-2	FalconSat-2
GSFC	Goddard Space Flight Center
HH	Hitchhiker
MESA	Miniature Electrostatic Analyzer
MS	Margin of Safety
NASA	National Aeronautics and Space Administration
PES	Pallet Ejection System
psi	pounds per square inch
PSD	Power Spectral Density
QM	Qualification Model
RMS	Root Mean Square
SVP	Structural Verification Plan (USAFA-FS2-SVP-01)
USAFA	United States Air Force Academy